

## Kinematic Modeling of a 6 Degree of Freedom Tri-Stage Micro-Positioner

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### Abstract

The 6-Degree of Freedom Tri-Stage Micro Positioner (6DFTSMP) can generate high accuracy, small displacement, and high-resolution motions. The moving platform of the device has six degrees (6-D) of freedom motions (translation and rotation about three orthogonal axes, X-Y-Z). The 6DFTSMP is unique because it derives its input motion from a monolithic tri-stage base plate and has struts that may have specially designed flexures. The 6DFTSMP capitalizes on the availability of inexpensive high quality planar micro-positioning stages for the control of its moving platform. Because the struts, which connect the planar micro positioning stages with the moving platform are oriented in a parallel mechanism fashion the in plane motion of the stages is converted into a translation and rotation about three orthogonal axes. Two experimental prototypes of the 6DFTSMP have been built and various mathematical models have been developed. A micro-position and orientation measurement sensor nest has been developed, which will be used to test various calibration and performance testing methods for this type of micro-positioners.

### Introduction

Opto-Electronic Manufacturing and Assembly is quickly becoming part of the critical path in advancing the manufacturing practices of many photonic manufacturers. Without reliable and inexpensive solutions to their manufacturing needs, many of their advanced photonic designs and products will be impractical for production and consumer applications. Usually manufacturing has been overlooked and is an after thought in the development of advances in industry. A critical component of Opto-Electronic Manufacturing and Assembly is the micro-positioner. A reliable, easy to calibrate, five to six degrees of freedom micro-positioner can significantly enhance the alignment and assembly of Opto-Electronic devices. The focus of the work we report in this paper is the development of sensors, calibration and performance testing techniques for parallel mechanism micro-positioners, like the 6DFTSMP.

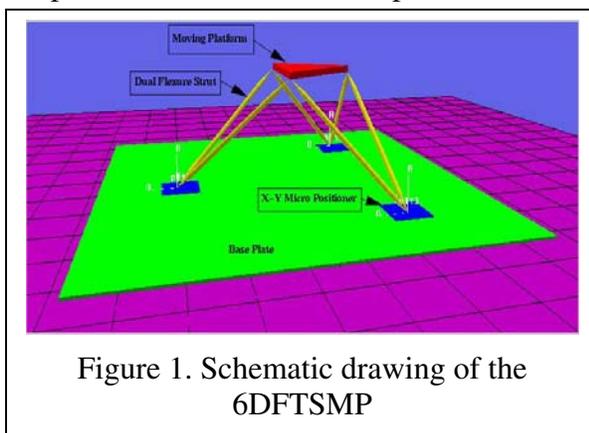


Figure 1. Schematic drawing of the 6DFTSMP

Figure 1 shows a schematic drawing of the 6DFTSMP with struts, which have flexures at both attachment points. The device consists of a base plate, six struts and a moving platform. The base plate is equipped with three X-Y micro positioning stages. Each of these stages is capable of generating motion in two orthogonal directions. The range of these motions depends on the design and size of these stages. The moving plate of each X-Y stage supports two struts, which are firmly attached to the plate on one end and the moving platform on the other

and allow motion to take place through elastic deformation of the struts and their flexures thus eliminating backlash and stiction. The moving platform is the load carrying part of the device.

The coordinates of the base plate support points of the struts form the base of the 6DFTSMP. The size and shape of the 6DFTSMP base changes, the struts deform, and the position and orientation of the moving platform changes when the moving plate of each X-Y stage moves. With proper calibration and sensors it is possible to control the position and orientation of the moving platform by commanding appropriate displacements of each X-Y stage moving plate. The three X-Y micro positioning stages are machined on the monolithic base [1]. This simplifies the design and makes the 6DFTSMP more compact. Also the use of a monolithic actuating base and a deformable three dimensional parallel mechanism structure eliminates backlash and stiction during motion. Because the actuation of motion takes place at the base there is no inherent limit to the size of the micro positioning stages, thus permitting a wider range of motion of the moving platform.

### Experimental Prototypes

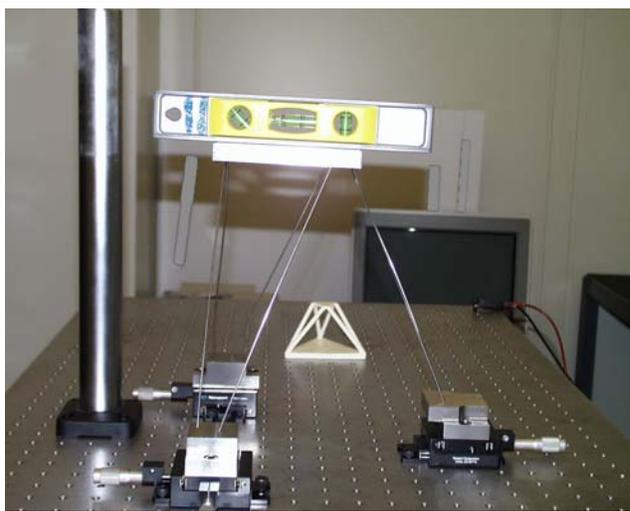


Figure 2. Steel wire 6DFTSMP prototype

Two functioning experimental prototypes have been constructed. Figure 2 shows a prototype that uses six Steel wire struts. The base plate X-Y micro positioning stages are simulated by three manual micro-meter stages. The use of these stages allows us to vary the size of the base plate without having to build one every time we make a change. Depending on the length and the diameter of the wires it is possible to achieve significant translations and rotations of the moving platform, as it is demonstrated in Figure 2. Because the wires act as parallel actuators the stiffness and payload capacity of the micro-positioner can be significant too.

Figure 3 shows the second prototype that uses six 6.35 mm (0.25 in) diameter steel rod struts. The base plate X-Y micro positioning stages are simulated by three motorized stages. The steel rods have their diameter reduced to 1.53 mm (0.006 in) at both ends, which are then attached to the base plates and the lower side of the moving platform. The reduction in the rod diameter forces the strut deformation to take place near the strut attachment points while the strut rod remains virtually rigid. A simple digital controller has been developed, which uses data from the kinematic models of these experimental prototypes to drive the X-Y micro positioning stages that result in a rotation and translation of the moving platform.

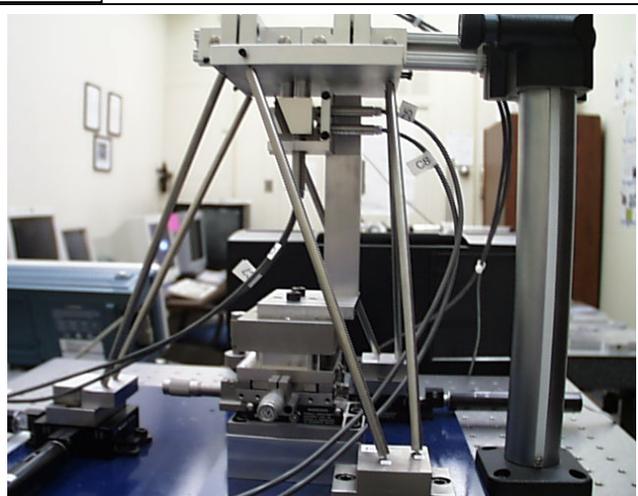


Figure 3. Steel rod 6DFTSMP prototype

### Micro Translation and Rotation Sensor

A good calibration requires a sensor that will measure the position and orientation of the moving platform stage. This is not a trivial operation especially when some applications might require accuracy of the order of 1 micrometer or less.

It is always possible to use several laser interferometers and autocollimators to measure the components of translation and rotation of the moving platform. This type of sensor though will be difficult to setup and very expensive. We needed a relatively simple, low cost sensor that can be used by manufacturers and users to calibrate and check the performance of 6-D micro-positioners. The solution was to modify a robot metrology sensor [2] to meet the above mentioned requirements. Based on our experience from the calibration and performance of planar micro-positioners we were able to build a compact sensor that can be installed and removed in a few minutes and which can serve an additional important function to protect the mechanism from overloading. Overloading can result from excessive actuator torque or impact with another object, like for example a robot arm. The sensor can be seen in Figure 3 underneath the centroid of the moving platform.

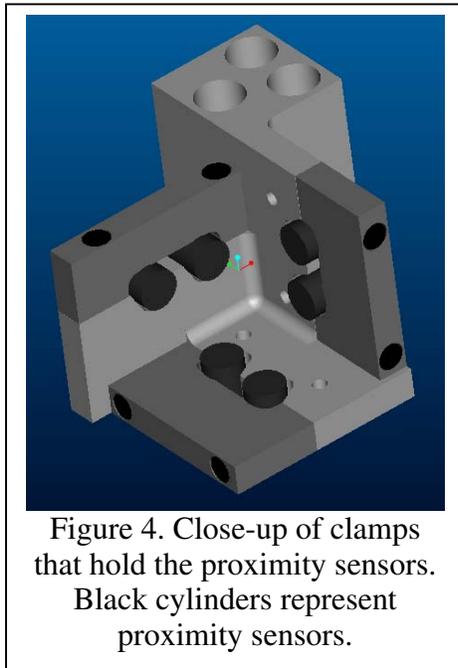


Figure 4. Close-up of clamps that hold the proximity sensors. Black cylinders represent proximity sensors.

To avoid interfering with the motion of the moving platform we decided to use non-contact proximity sensors. The main choices are capacitive gages and opto-electronic reflective sensors. The capacitive gages are excellent proximity sensors, but can cost 10 times or more the cost of opto-electronic reflective sensors.

The reflectors of our sensor are the polished sides of a true square cube. The cube has five highly polished reflecting sides orthogonal to each other within 3 arc seconds. The sixth side has three tapped holes for mounting underneath the moving platform. The cube is attached to the lower side of the moving platform plate and translates and rotates with the platform as a single rigid body. Three orthogonal adjacent sides of the cube face three orthogonal adjacent plates of a sensor nest (see CAD image in Figure 4) mounted on a beam, which is attached to the base plate through an X-Y-Z position adjustment stage. The sensor nest remains stationary while the cube moves with the micro-positioner moving platform. Two proximity sensors are mounted on each sensor nest plate

with their sensitive front side facing the moving cube. The six distance signals from the sensors can be combined to estimate the position and orientation of the moving platform reflecting cube rigid body with respect to a sensor nest reference coordinate frame. Each sensor nest plate consists of two parts, a plate with two V shape groves and a clamp. The proximity sensors are placed in the V shape groves and are held in place by the clamps. Loosening the screw that corresponds to each proximity sensor allows adjustment of its position until the desired output signal is detected. The sensor nest has to be calibrated first and then used to calibrate the micro-positioner. Once the sensor nest is calibrated epoxy glue drops are used to detect any change in the position of the proximity sensors within the sensor nest.

### Kinematic Models

Kinematic mathematical models have been developed for two different versions of the 6DFTSMP. The intersecting struts design and the non-intersecting struts design. Figure 1 shows an example of an intersecting struts 6DFTSMP. In that case the neighboring struts are joined at

the center of their upper and lower flexures and then attached to the base plate and the moving platform. Figure 3 shows an example of a non-intersecting struts 6DFTSMP. In that case the struts are attached to the base plate and the moving platform at separate points, which are determined by the desired geometry of the mechanism. The objective of our work is to develop calibration and performance testing techniques for a variety of these designs. At this stage our calibration effort is focused on the identification of the parameters of kinematic and dynamic mathematical models of the micro-positioners and the use of the performance tests to evaluate the accuracy of these models. Since it is not possible to fully predict the shape of the deforming 6DFTSMP under various loading conditions it will take several iterations in order to come up with models that meet tight performance specifications. These models are necessary for the control of these type micro-positioners and for the detection of defects that are difficult to detect by simple inspection, like for example plastic deformation of strut flexures.

The most simple of the mathematical models is that of the intersecting struts 6DFTSMP. It can be shown that the coordinates  $d_{ix}$ ,  $d_{iy}$ , of the base plate attachment points for  $i = 1, 2, 3$ , with respect to the base plate coordinate system are given by:

$$(s_{ix}^2 + 1)d_{iy}^2 + 2\left(s_{ix}(h_x + p_{ix}) - (h_y + p_{iy}) - q_{ix}s_{ix}\right)d_{iy} + (q_{ix}^2 - 2(h_x + p_{ix})q_{ix} + g_i) = 0 \quad (1)$$

$$d_{ix} = q_{ix} - s_{ix}d_{iy} \quad (2)$$

Where  $p_{ix}$ ,  $p_{iy}$ , are the coordinates of the three moving platform attachment points and  $h_x$  is the X-axis coordinate of the centroid of the moving platform.  $s_{ix}$ ,  $q_{ix}$ ,  $g_i$ , are complex functions of the kinematic parameters of the mechanism, which cannot be listed here due to the page limitation, but will be described in later publications.

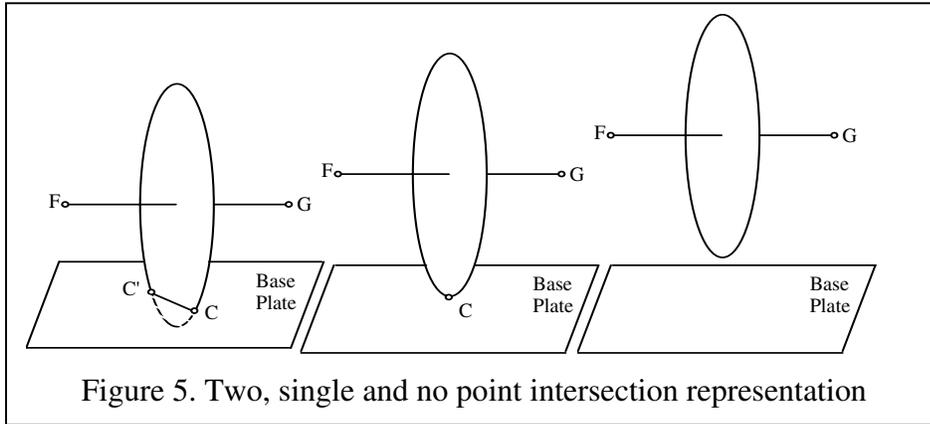


Figure 5. Two, single and no point intersection representation

Equation (1) can have two, one or no solutions. This is depicted by the three schematic drawings of Fig. 5, where F and G represent moving platform attachment points and C, C' solutions.

#### References

1. Amatucci E., Dagalakis N.G., Kramar J.A., Scire F.E., "Performance Evaluation of a Parallel Cantilever Biaxial Micropositioning Stage," ASPE 2000 Annual Meeting, Oct. 22-27, 2000, Scottsdale, Arizona.
2. Ranky, P. G. "Test Method and Software for Robot Qualification," The Industrial Robot, pp. 111-115, June 1984.

#### Acknowledgements

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